Riders On The Storm:
NASA InSight Lander and the 2018 Mars Global Dust Storm

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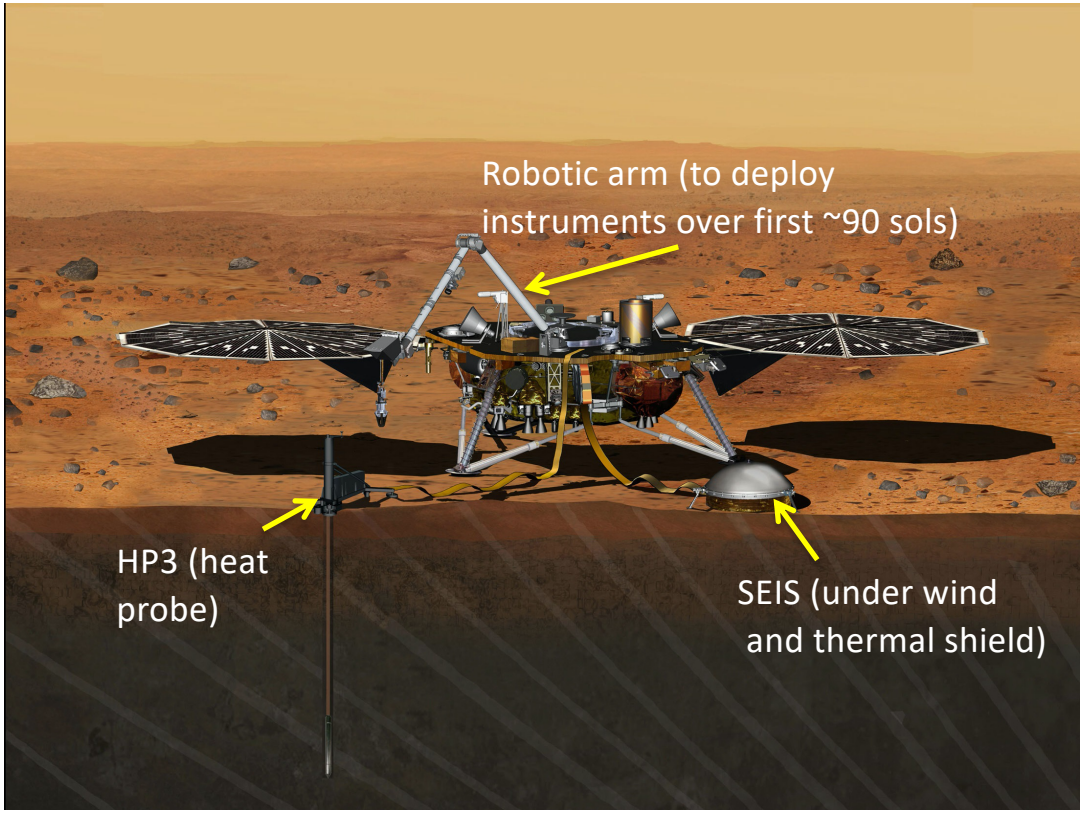
Prologue

- Mars Global Dust Storms:
  - Have been seen in astronomical and Mars mission data to happen on average every 3 Martian years (~6 Earth years)
  - Have been seen to take place between Mars solar longitude (Ls) values of 180 deg to 360 deg (Northern fall and winter)
    - Conversely, from Ls = 0 to 179 degrees, global or large regional dust storms have not been seen to occur
- InSight inherited –and was constrained to work with - the 2008 Phoenix mission's successful Entry, Descent and Landing design
  - Phoenix lander fit snugly inside its aeroshell and sized, mass-wise, to survive entry heating, be successfully slowed by its parachute, and land successfully with its radar and retrorockets
  - InSight was constrained in mass and volume to not break the Phoenix EDL design
  - Phoenix landed near the Martian north pole after the Global Dust Storm season was over, and operated for ~150 Martian days …
  - But InSight would land near Mars equator during the Global Dust Storm season, and needed to operate for more than a Mars year

InSight Solar Powered Spacecraft Deviated from Phoenix Design



- InSight Entry, Descent and Landing (EDL) design modestly changed from Phoenix – esp. thickening of thermal protection ablative vs dust erosion.
  - Focus of this presentation will be *surface power*, as InSight EDL reconstruction is ongoing
- InSight is first solar-powered Mars lander designed to operate for an entire martian year.
  - 2 solar arrays (totaling ~5 m^2 collecting area) with triple-junction photovoltaics
  - 2 Li-ion batteries (unlike MER, no radioisotope heaters to warm the batteries)

Phoenix in ATLO (2006-2007); InSight in ATLO 1.0 (2015)

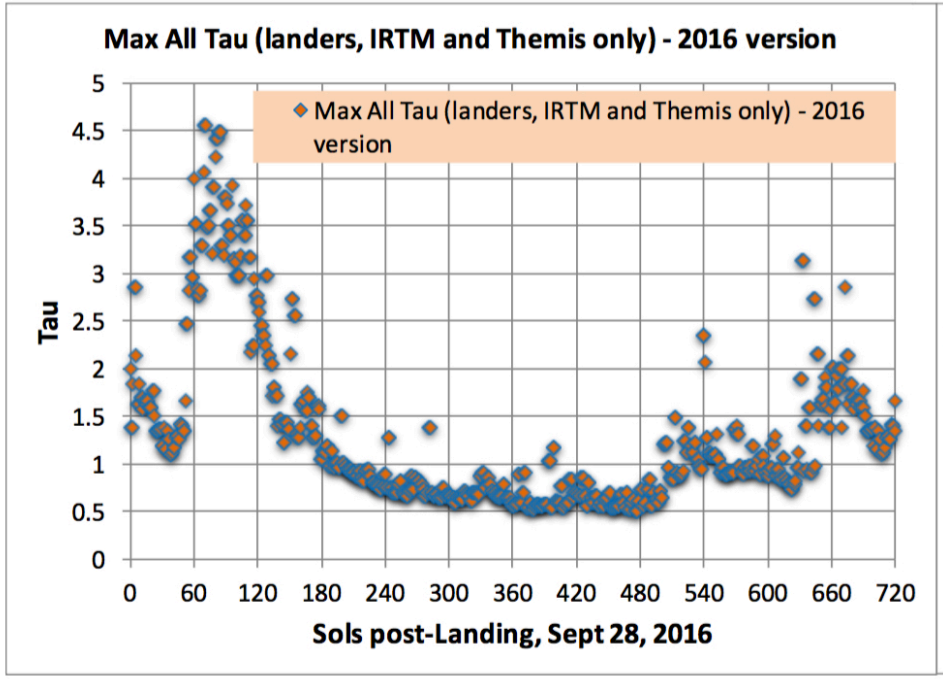
Phoenix

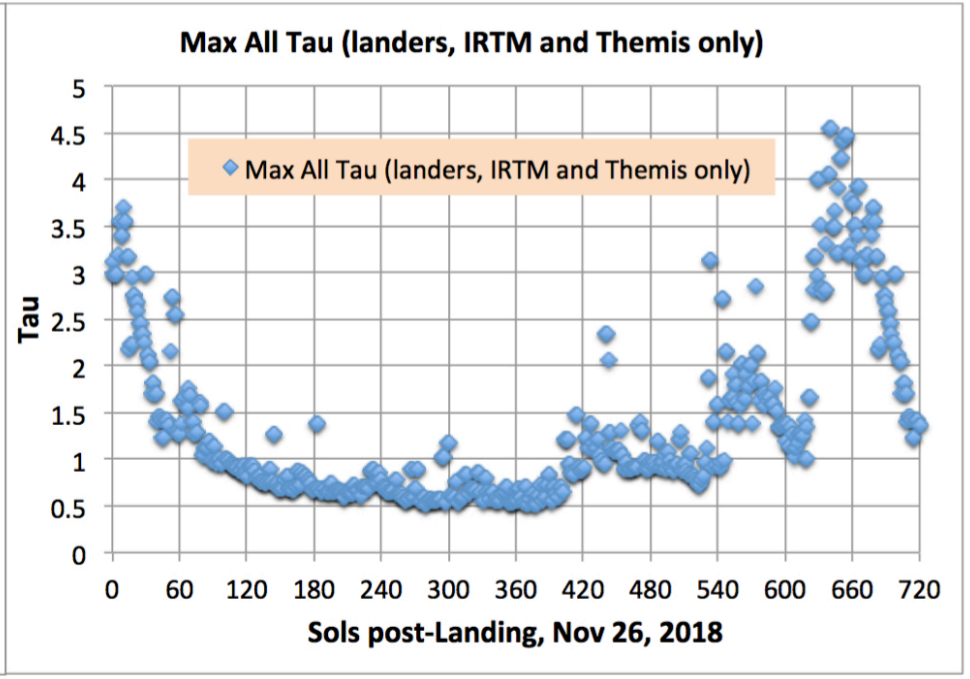
InSight

Phoenix vs InSight Design Environment Requirements for Surface Energy

Item	Phoenix	InSight
Max design Latitude	72 deg N	5 deg N
Min design Latitude	65 deg N	3 deg N
Design Range of Mars Orbit Solar Longitude Ls	76 – 125 deg (90 sol mission)	0 – 360 deg (1 Mars-year plus mission)
Landing Season	Ls 76 deg (northern spring)	Ls 295 deg (northern winter)
Surface Mission Design Duration	90 sols	709 sols
Max design dust storm optical depth “tau”	2.50	4.6 “worst observed by MER, Viking Landers, IRTM or Themis”
Maximum temperature (1-m air)	-18C	-3C
Minimum temperature (1-m air)	-87C	-99C
Maximum Number of Sols in Dust Storm Survival	3 sols (per PHX ERD)	120

2018 vs 2016 Dust Storm Almanac Worst-observed Tau per Sol





- Key requirement from Phase B (~2013) for InSight surface energy was ability to operate (or survive) in the worst-observed tau for on any day of the mission.
  - The "worst-observed" came from the InSight Dust Storm Almanac, which maps to InSight post-landing sol the worst values of tau (vs Ls) measured on the surface by Viking landers, MER or MSL, or from orbit by Viking orbiter IRTM and Mars Odyssey Themis instruments, for which surface-based tau calibration could be done. (*Subject of 2014 IEEE paper*).
  - Other requirements: also operate (or survive) under worst-case solar array tilt for power (12 deg to North or South), and under a conservative solar array dust accumulation profile assuming no wind cleanings.
- The hiatus with its new landing date resulted in a new landing solar longitude Ls - was: 231 deg; is: 295 deg. (*Subject of 2017 IEEE paper*).
- We were now landing during the "tail" of the dust storm season, but saw the historic storms rise up several months before the end of our 1 Martian year (compare plots above).

InSight Lifts Off 5/5/2019, Starting Its 6.5-month Cruise to Mars

Then, One Month Later …

- On June 5, 2019, as InSight was traversing interplanetary space towards Mars, the long-lived Opportunity Rover (MER-B) at Meridiani Planum on Mars was enshrouded by a fast-moving and utterly *ginormous** dust storm.
  - She sent back an optical tau measurement and was heard from no more.
- Recent recalibration of Opportunity's last optical measurements have confirmed that tau that sol was **11.** *Shades of Spinal Tap …*

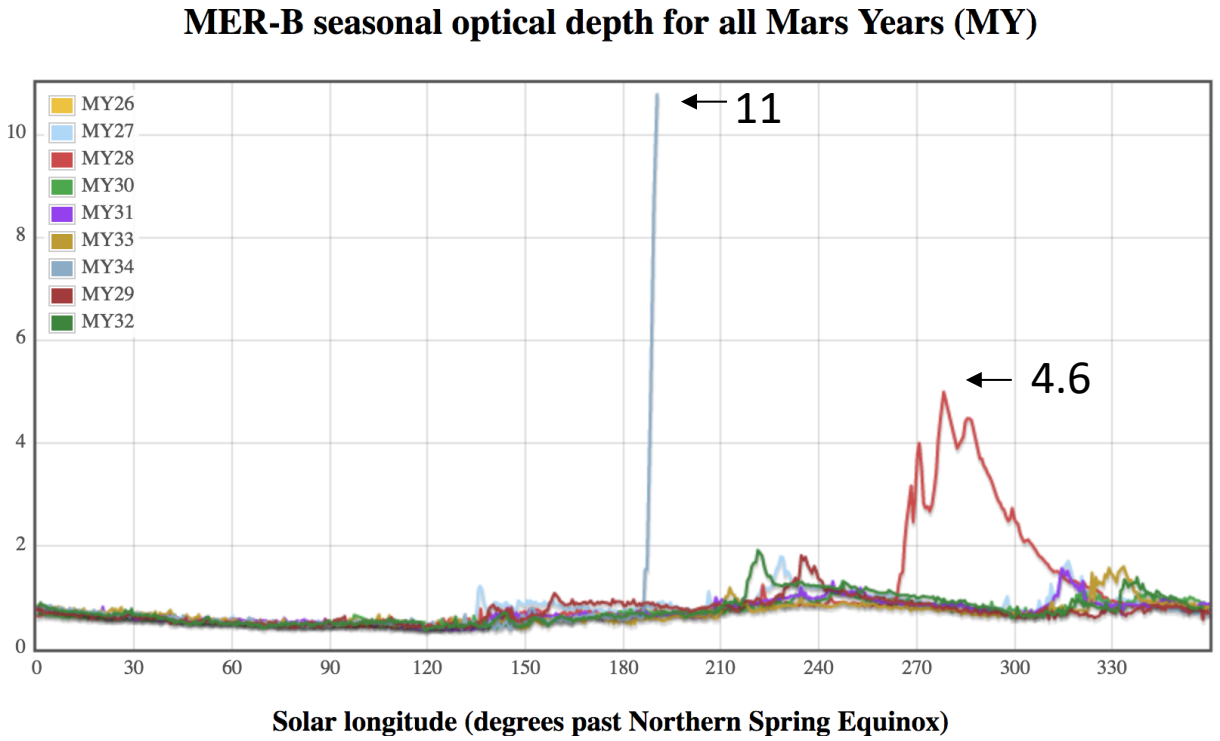


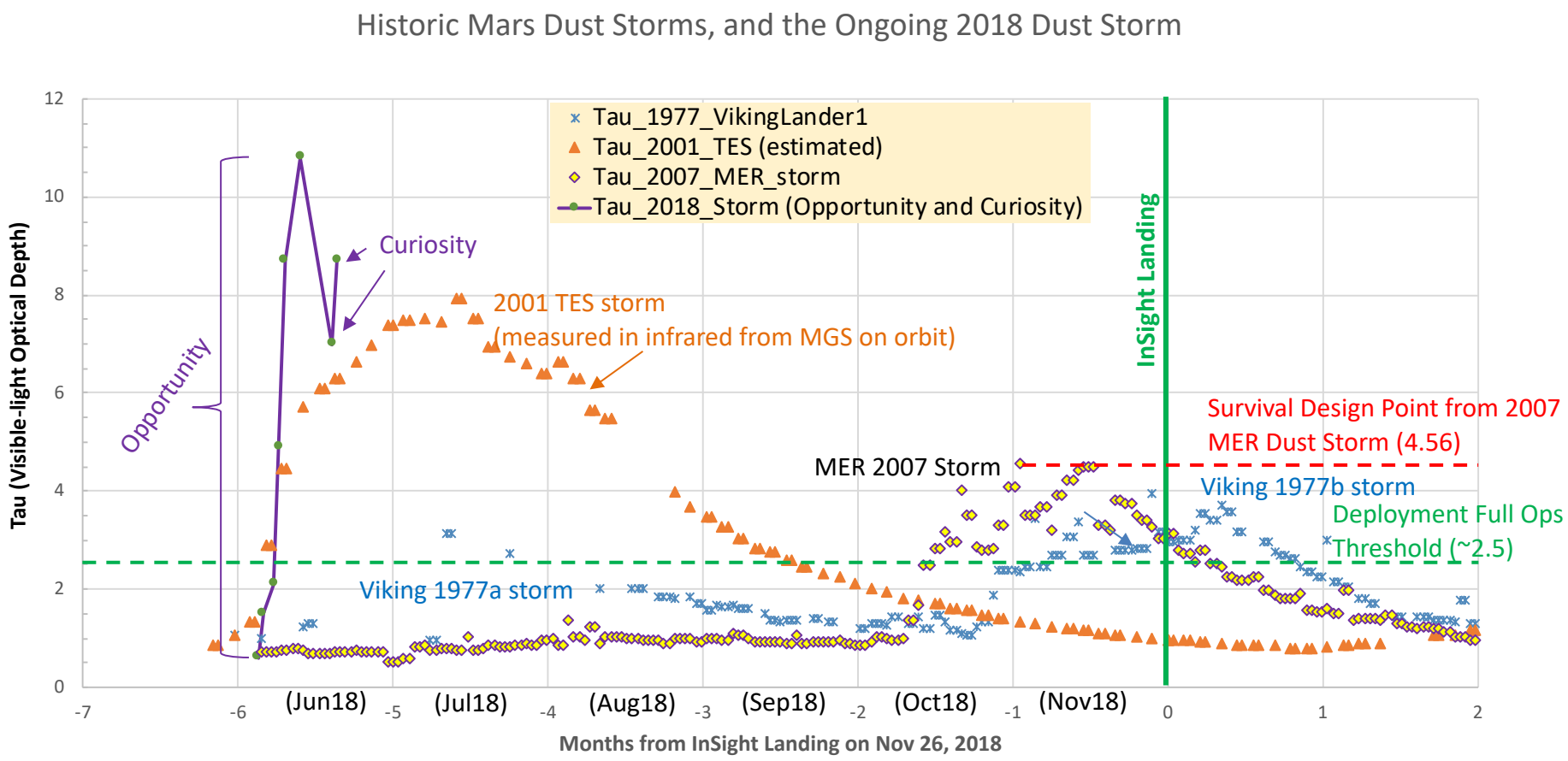
Image courtesy of Mark Lemmon Texas A&M

*My 15-year-old son assures me this is, in fact, a word

So Now What?

- Light extinction goes as e^{-tau}, so a tau of 11 is clearly far worse than InSight's maximum tau spec of 4.6. ~1000 x darker
- It was noted that the Opportunity storm had started to rise up right at about solar longitude Ls of 180 deg.
  - Some stated it was the earliest a big dust storm had ever been seen rising up and that it might "go global"
  - They were half right; this storm would become a global storm.
  - In the InSight dust storm almanac, we had records on another global storm that had no surface asset calibration
    - That global storm rose up in 2001 at about Ls 180 deg, measured by the TES instrument on Mars Global Surveyor
    - Some interpretations of its uncalibrated, down-looking infrared tau estimates were that it had gotten as high as 8 or 9 (others suggested only 3-4).
    - As "now what" calls came from "concerned folks" about the 2018 storm, it had become time for a fresh look back at that 2001 storm …

2018 Storm vs Other Storms, In Seasons They Occurred



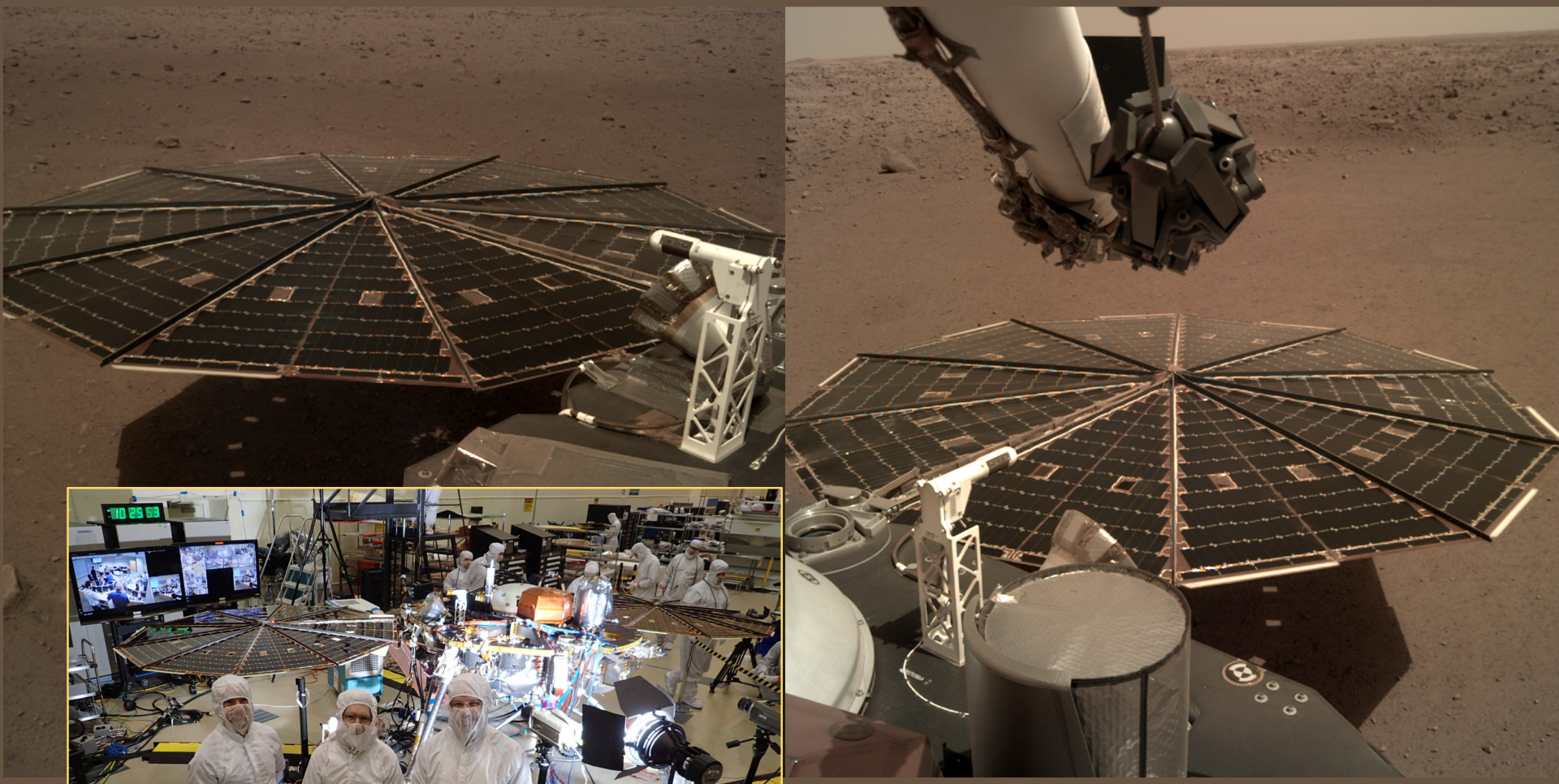
- The 2018 storm rose up with similar seasonal timing and rate as the global storm of 2001.
- We saw InSight would land after the 2018 storm likely would fade below InSight's survival design point.
- Still-elevated tau levels – if present - when InSight landed could result in either safe mode or slower-paced deployment.

Lessons Learned (two of them)

1. Mars can be rather mean sometimes
2. Having a well-studied and carefully cross-calibrated, reviewed database on all previously measured dust storms helps to assess the situation rapidly
   - The InSight Dust Storm Almanac, which we created back in Phase B, was still doing an important job for us after launch
     - Helped not only power, but also our EDL team, to keep abreast of the storm and have some expectancy in the out months before landing
   - Provided a crucial comparative basis to grasp this new storm's impact on us, as a function of tau and time till landing

What Happened Next?

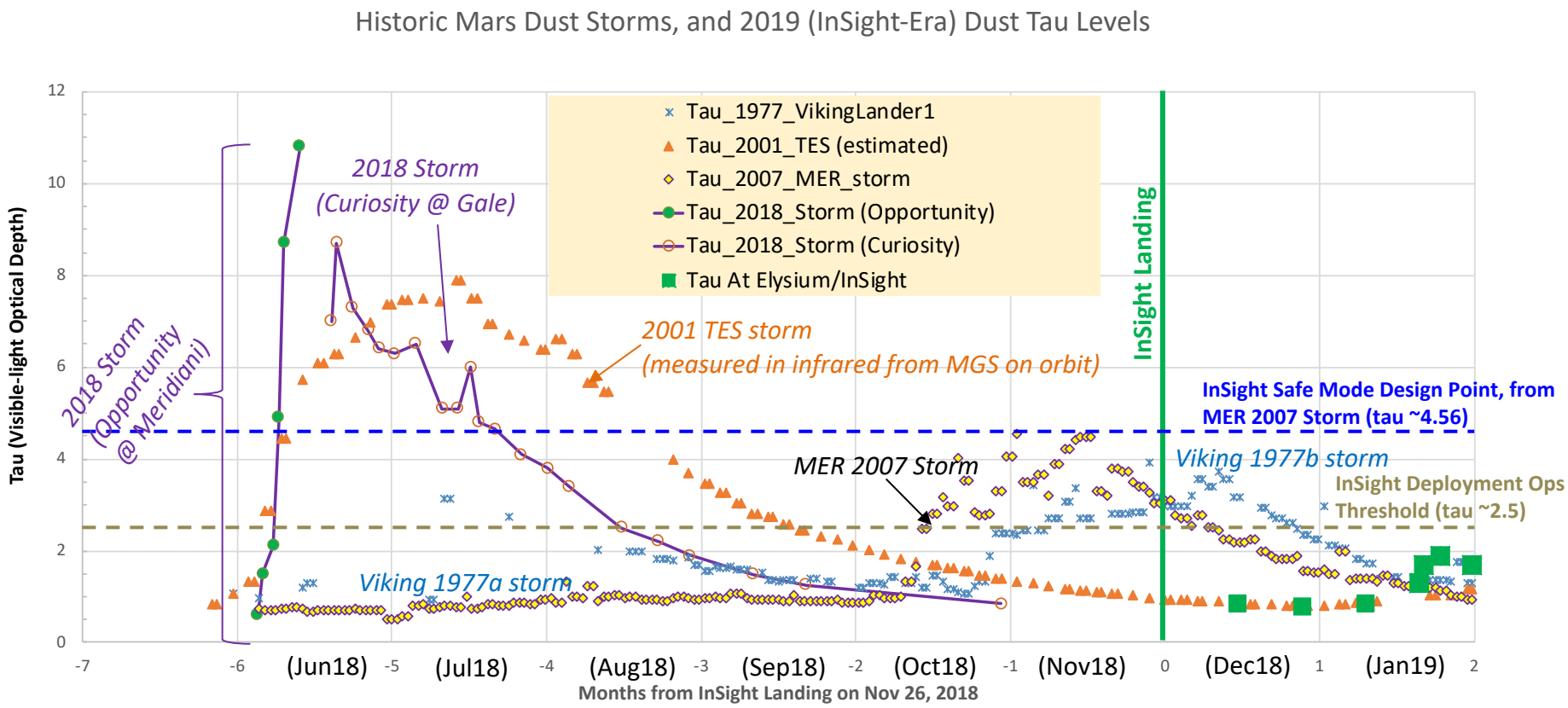
- The 2018 storm abated to a safe level for InSight EDL and surface energy by mid-August 2018.
- A few months later, on Nov 26, 2018, InSight landed safely at a benign, relatively-rock-free site that was ideal for our science.
- And tau was about 0.8, very clear skies.
- Our dust-free solar arrays were generating **4607 Watt-hours** per Martian day (sol), more than we'd predicted best-case during ATLO (lots of conservative margins in the solar array loss terms)
  - Maximum per-sol energy production of other Mars landed assets were:
    - Curiosity Rover (radioisotope) – **2806 Wh**
    - Phoenix (solar) **~ 2800 Wh**
    - Spirit and Opportunity (solar) – **994 Wh (Spirit), 922 Wh (Opportunity)**
    - Mars Pathfinder (solar) – **1200 Wh (Lander), 100 Wh (Rover)**
    - Viking (radioisotope) **~ 860 Wh**
- Soon after the seismometer was deployed to the surface, a marked increase in tau occurred, lowering power production by a lot – daily energy margins stayed safely above 30% each sol.



Apr 30, 2015 – 1st Solar Array Deployment Test
Lockheed Martin, CO (InSight ATLO 1.0)

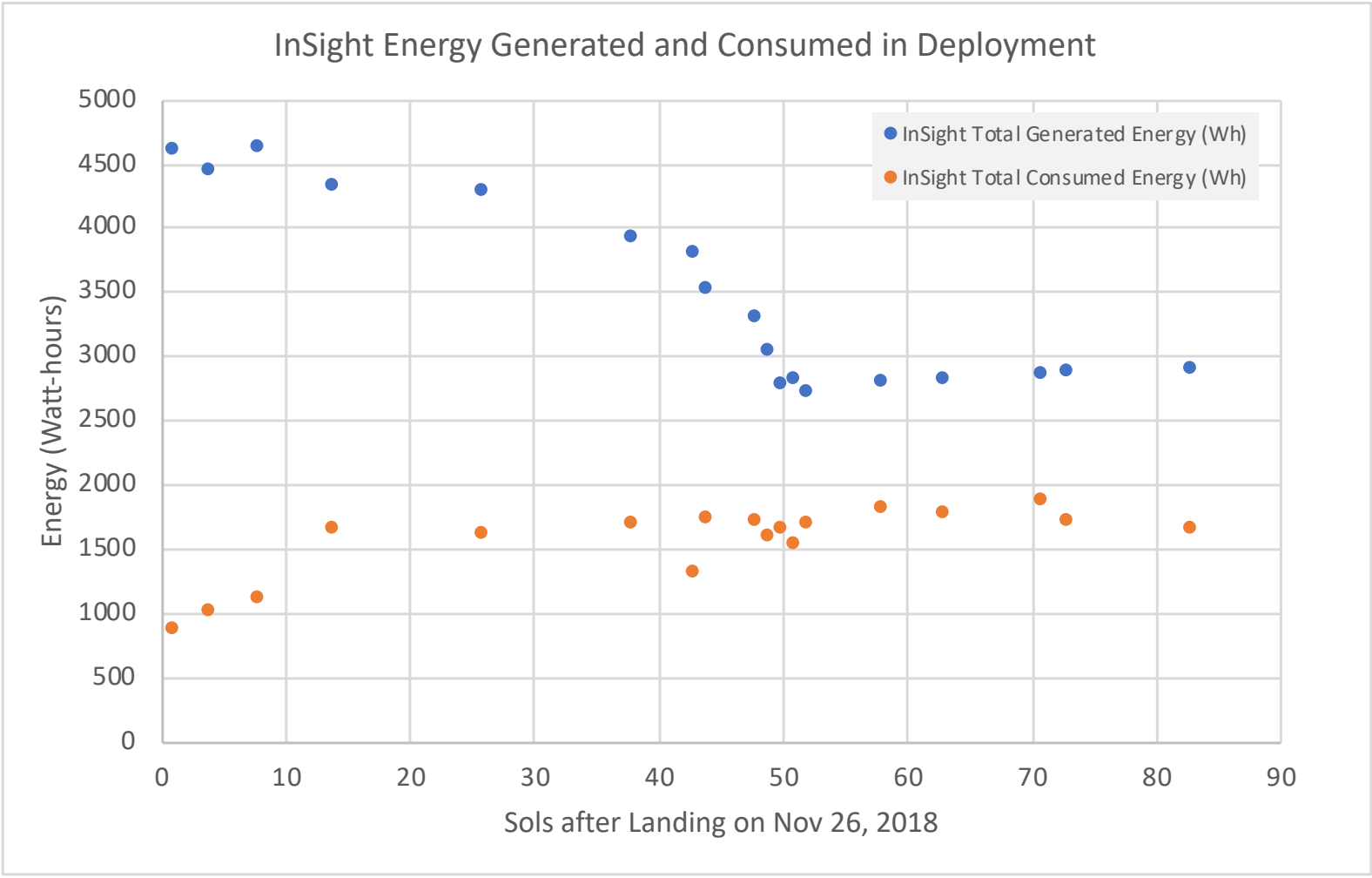
Dec 6, 2018 – first full images of deployed arrays
Elysium Planitia, Mars

"Tau and Dust Storms" for InSight



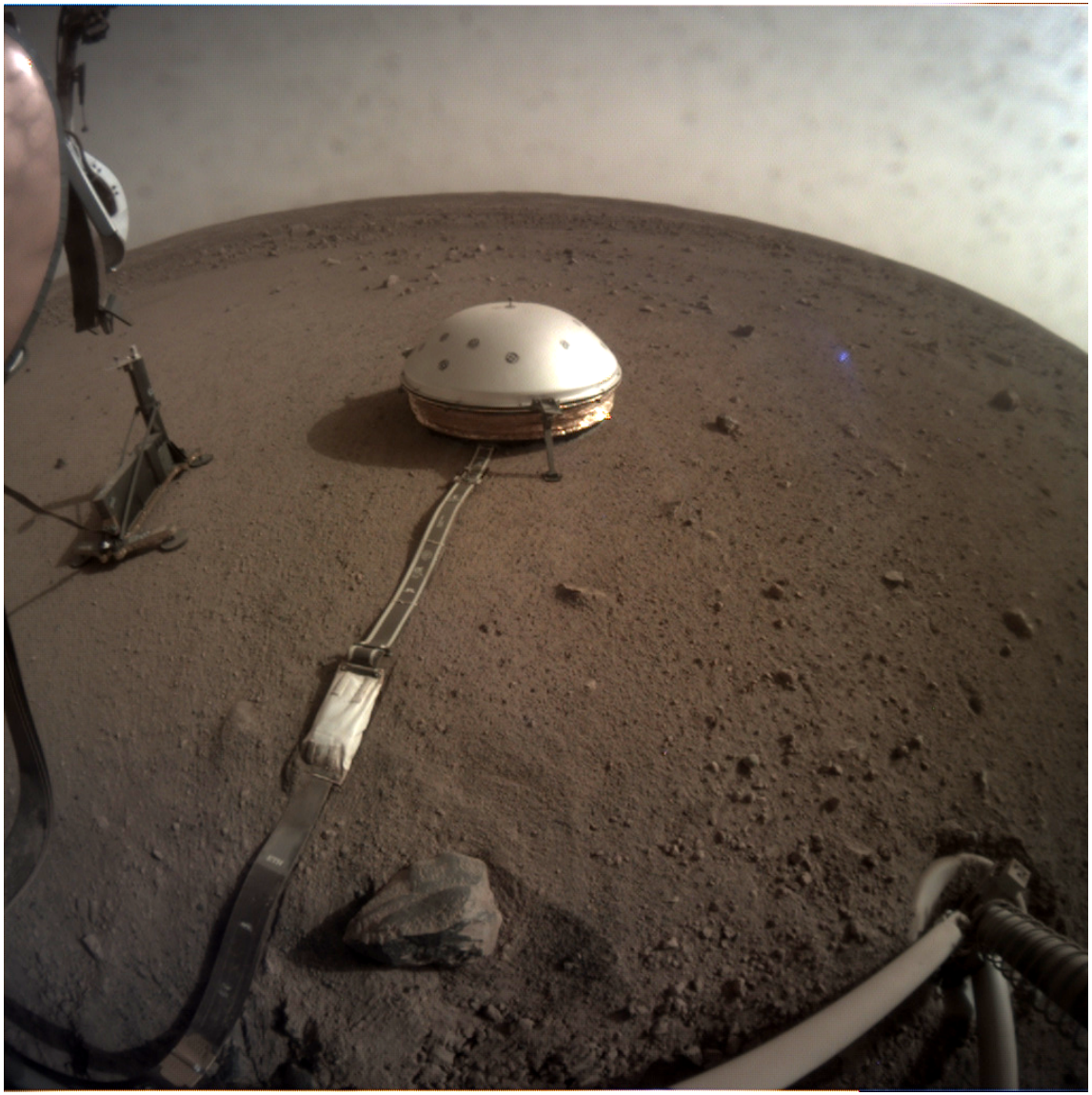
In-situ tau observations at Elysium: **7 green squares** (from InSight sols 14, 26, 38, 48, 49, 52, and 58).

Energy Performance, InSight Sols 0 – 83



InSight has retained daily energy balance through deployment with margins of 900 W-hr or greater.

InSight Station at Elysium as of Feb 20, 2019 (Sol 83)



Conclusions and More

- Next steps – getting the mole 5 meters underground, and “listening” for a Mars year to the interior of Mars
  - Energy management and spacecraft power, as well as the science team, will keep an eye on dust accumulation on the solar arrays, and adjust onboard activities to manage loads

- Suggestions for future solar-powered missions to Mars surface, now that we’ve seen a tau of 11, in a global storm that lasted > 2 months:
  - Think carefully on your mission’s arrival time and timeline, with the storm seasons in mind
  - Consider how to survive a months-long power fault in ultra-high tau
  - Consider array-cleaning technologies to manage heavy, rapid dust-fall

- The authors thank the innumerable members of the InSight engineering and science teams: launch, cruise, EDL and surface ops; past and present; who have helped make this mission a very exciting reality!